AUBE '01

12TH INTERNATIONAL CONFERENCE ON AUTOMATIC FIRE DETECTION

March 25 - 28, 2001
National Institute Of Standards and Technology
Gaithersburg, Maryland U.S.A.

PROCEEDINGS

Editors: Kellie Beall, William Grosshandler and Heinz Luck

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

David Bomse
Southwest Sciences, Inc., Santa Fe, NM, U.S.A.

A Diode Laser Multigas Analyzer for Advanced Detection of Fires

1. Introduction

An ideal instrument for early fire detection would combine high sensitivity, rapid response, automatic self-testing and a low false alarm rate while generating information specific to the location and nature of the fire. Current fire detection strategies in large buildings call for many point sensors such as standard smoke detectors. In these systems, the false alarm rate becomes unacceptably high because the overall rate is the sum of the false alarm rate from each sensor. Even if sensors are inexpensive, routine maintenance and testing can be very costly when hundreds of detectors are in use. Some new systems use multiple point air sampling and a centralized, highly sensitive smoke detector; this approach reduces false alarm rates but is expensive to install, particularly in existing structures.

Near-infrared diode lasers allow detection of trace gases by optical absorption spectroscopy. It is possible to provide rapid, part per million (or better!) quantitation of combustion products including CO, HCN, HCl, CO_2, CH_4, acetylene, HF, and perhaps formaldehyde. Detection of incipient fires is possible. The approach being studied shows high selectivity for each gas detected; the concentration of each species is measured separately. False alarm rates can be reduced dramatically because a positive indication of a fire requires observing higher than normal concentrations of more than one target gas.

The type of diode lasers useful for fire sensing was originally developed for long haul fiber optic communications. These miniature devices are rugged, reliable, operate at low power, and require absolutely no maintenance. Near-infrared diode lasers are compatible with conventional, inexpensive fiber optics. Thus, we envision a fire sensing system in which the light from several lasers housed in a central location is distributed via a fiber optic system to hundreds of remote measurement locations. Feasibility calculations imply that light from one laser can be distributed among 800 such measurement points.

Most implementations of our diode-laser-based fire sensing technique will rely on simultaneous quantitation of three or four key gases selected from carbon dioxide, carbon monoxide, hydrogen cyanide, hydrogen chloride, and acetylene. Carbon dioxide is included because it provides a known non-zero background level that can be used as a continuous check of instrument operation. This solves one of the problems found with instruments designed to report rare events: how to provide frequent verification of proper operation? Carbon dioxide levels will fluctuate, but it is unreasonable to expect the concentration to drop significantly below 350 ppm. Such a loss of signal would be indicative of system error. Carbon monoxide and hydrogen cyanide are particularly important because these gases are implicated in most smoke inhalation deaths.[1-4] Hydrogen chloride is a key signature compound produced during pyrolysis and combustion of PVC-containing plastics.[5] Acetylene is a soot precursor. In addition, detection of HCN, HCl, and HCCH is useful for fire sensing because all of these compounds have extremely low background levels in nearly all environments. Finally, measuring CO and CO_2 levels may also prove useful for indoor air quality monitoring and can be incorporated into energy conservation schemes for building-wide HVAC systems.

Initial experiments demonstrated that modulation frequency multiplexing is the optimum method for simultaneous (or near simultaneous) detection of multiple gases. In this approach, one laser is used for each gas detected. The output from each laser is combined into a single optical fiber. It is possible, however, to distinguish the signals due to each laser–hence the concentration of each gas–by modulating each laser at a slightly different frequency. Selective demodulation of the photodetector output allows discrimination among the absorbance signals. This approach is similar to radio where a tuner picks out one station among a myriad of broadcast signals.

Our current research is building on these results by constructing and testing a prototype system for simultaneous detection of CO, CO_2, and HCN. It should be possible to build rugged, reliable, multigas sensors for the detection of incipient fires. Output from each laser can be distributed to hundreds of measurement locations using a fiber optic distribution network.

2. Gas Detection Using Near-Infrared Diode Lasers

For diode-laser-based fire detection, the sensitivity toward each compound is determined, in large part, by the smallest optical absorbance that can be measured. Absorbance, α, is a dimensionless quantity defined by Beer's Law,

$$\frac{I}{I_0} = e^{-\alpha} \text{ where } \alpha = \sigma N \ell, \quad (1)$$

where I is the laser intensity reaching the detector, I_0 is the laser intensity in the absence of absorption, σ is the absorption cross section, N is the number density of the absorbing species, and ℓ is the absorption path length. Since absorption cross sections and optical path lengths are known, measurement of absorbance allows determination of concentration. Conventional spectrometers such as FTIR instruments or diode array devices can measure absorbances down to $\alpha \sim 10^{-3}$, whereas using diode lasers we and other groups[6-19] have demonstrated minimum detectable absorbances as small as 10^{-7}. For the deployment scheme planned for fire detection, where the laser output is distributed among many measurement points, the *theoretical* lower bound is defined by laser/detector shot noise and equals a minimum detectable absorbance better than 10^{-6} (1 Hz bandwidth). We estimate that each of the optical measurement locations in our fire detection scheme will achieve minimum detectable absorbances of 10^{-5}.

The detection method we employ with diode lasers is a high frequency version of what is described in the literature by the terms "wavelength modulation spectroscopy," "derivative spectroscopy," or "harmonic detection." [6-14] The absorbance measurement is shifted to high frequency to avoid laser excess ($1/f$) noise. A small sinusoidal modulation is superimposed on the diode laser injection current. This current modulation produces a modulation of the laser wavelength, since the laser wavelength is tuned by changing the current. As the laser beam passes through the sample gas, absorption converts the wavelength modulation into amplitude modulation. The AM components of the laser intensity induce synchronous modulation of the photodiode current at the modulation frequency, *f*, and higher harmonics, n*f*. Phase-sensitive electronics isolate and quantify (demodulate) the photocurrent component at a selected harmonic. The demodulated signal

lineshape looks like the n^{th} derivative with respect to wavelength of the direct transmission spectrum. Absolute absorbances are obtained by dividing the demodulated AC signal by the detector DC output; high sensitivity absorbance measurements are possible using a single optical beam.

Another important advantage of wavelength modulation spectroscopy is that the technique responds only to the type of narrow, isolated absorbance features characteristic of gas phase compounds. Attenuation of the laser beam by particulates, or losses due to scattering do not generate false positive signals. Since the actual absorbance is proportional to the ratio of the AC to DC components of the detector output, measurements can tolerate a ten- to hundred-fold loss in overall light intensity (the DC signal), yet provide accurate gas concentrations. If the DC level falls below some predetermined minimum, then the instrument will report an error.

3. Characteristics of Near-Infrared Diode Lasers

Diode lasers are ideally suited to spectroscopic detection of gases because the lasers are wavelength tunable and are highly monochromatic. Coarse tuning can be accomplished by varying the laser temperature using an inexpensive thermoelectric cooler, which can be an integral part of the laser packaging. High resolution wavelength tuning is obtained by varying the laser injection current. AC modulation of the laser current is a simple method to implement wavelength modulation.

Gases important for fire detection can be detected using InGaAsP lasers which were originally developed for long haul, fiber optic communications. These lasers can be fabricated at any wavelength between 1.2 and 2.0 µm, and each device has a tuning range of about ±2 nm. This relatively limited tuning range requires a separate laser for each gas detected in most cases.

InGaAsP lasers operate at room temperature and are compatible with standard silica fiber optics and with high efficiency InGaAs photodiode detectors that also operate at room temperature. The lasers are hermetically sealed in miniature (approx. 1" × ½" × ½") DIP

or butterfly IC packages and consume less than 100 mW of electrical power while producing from 2 to 5 mW of near-infrared light.

Spectral purity of the laser output is important for gas detection applications. The simplest style of diode laser often emits several nearby wavelengths simultaneously and is not suitable for the proposed application. In the case of InGaAsP diode lasers, single mode (single frequency) operation can be obtained with distributed feedback or "DFB" lasers that include a grating etched along the gain region. The laser output has a wavelength spread of only 0.003 cm^{-1} compared with gas absorption linewidths of 0.1 cm^{-1}; in contrast, laboratory spectrometers such as FTIR devices typically show resolution of 1 cm^{-1}, or worse. Extremely narrow laser linewidths allow selective probing of a single absorption line, even in the presence of many other gases. This point is crucial to the success of the proposed fire detection technique: wavelength selectivity increases the sensitivity for detecting each target compound while also minimizing the risk of false alarms.

4. Feasibility Demonstration

Figure 1 is a schematic diagram of the apparatus first used to test modulation frequency multiplexing for simultaneous detection of multiple gases. The feasibility study focuses on simultaneous measurement of CO and CO_2 with a separate laser used for each gas. The CO laser is modulated at 50 kHz while the CO_2 laser is modulated at 40 kHz. Output from the lasers is injected into a single mode fiber using a 2 × 1 fiber optic beam combiner. The resulting light exits the fiber, is collimated by a graded index (GRIN) lens and directed into the Herriott [20] cell containing 50 torr each of CO and CO_2. After traversing 26 passes within the cell (13.9 m), the beam exits and is focused onto an InGaAs photodiode. Output from the photodiode is applied to

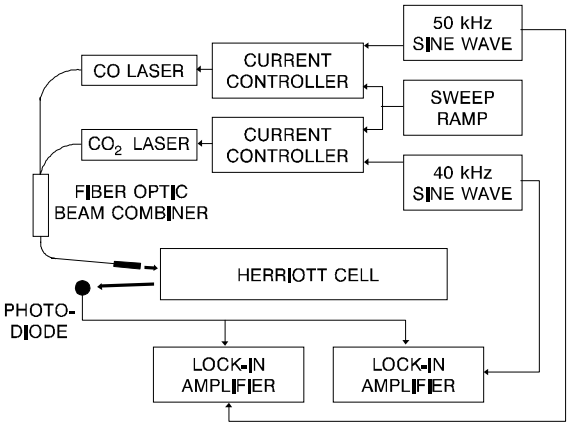

Figure 1 - Schematic diagram of apparatus used to test modulation frequency multiplexing for the simultaneous detection of two gases.

a pair of lock-in amplifiers set to operate at $2f$; one is referenced to the 50 kHz modulation source, the other to the 40 kHz source.

Wavelength modulation spectra are acquired by sweeping both laser current supplies and digitizing the output from the two lock-in amplifiers. The DC currents from each supply are adjusted such that the peak due to CO appears at the left hand side of each scan with the CO laser while the CO_2 peak appears at the right hand side of each scan with the CO_2 laser. This approach-scanning full wavelength spectra and offsetting the positions of the two peaks-is useful for determining signal-to-noise ratios and for examining potential cross-talk between the two absorbance measurements.

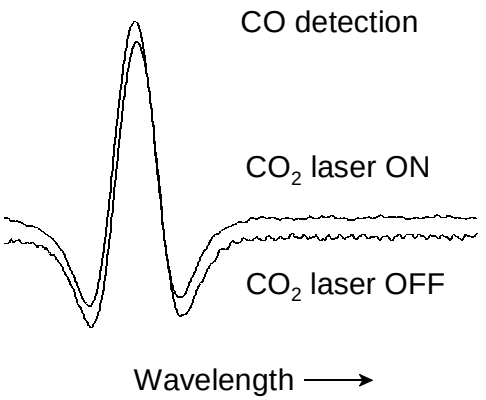

Figure 2 - Modulation frequency multiplexing detection of carbon monoxide in a 50:50 mixture of CO and CO_2.

Measurements show that the limiting noise source is not due to the multiplexing scheme but to unwanted optical interference fringes which change slightly in magnitude during the time required to collect all pertinent data. Specifically, Fig. 2 compares CO spectra taken when only the CO laser was on (lower trace) and when both lasers were on (upper trace). The WMS signal corresponds to a peak absorbance of 2.7% (measured in a separate experiment). We define the noise as the standard deviation of the right hand baseline region. Spectra in Fig. 2 imply that the minimum detectable absorbance changes from 1.2×10^{-5} when only the

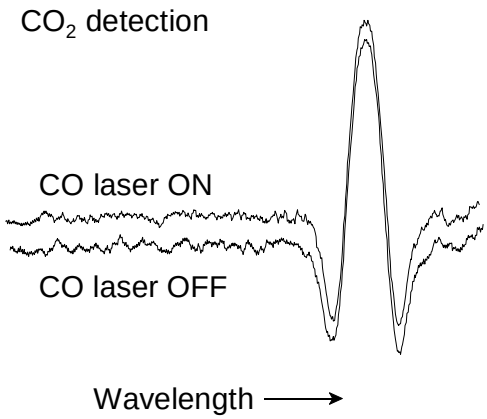

Figure 3 - Modulation frequency multiplexing detection of a carbon dioxide in a 50:50 mixture of CO and CO_2.

CO laser is used to 1.8×10^{-5} when both lasers are on. For these data, measurements are extrapolated from the 20 Hz bandwidth used to a 1 Hz detection bandwidth. In contrast, the data in Fig. 3, which shows CO_2 spectra, indicate the minimum detectable absorbance actually improves from 1.6×10^{-5} to 0.8×10^{-5} when the CO laser is activated.

Examination of the baseline regions in both sets of spectra, Figs. 2 and 3, shows that regular interference fringes dominate random noise. This feature is seen most clearly in the lower trace of Fig. 2. The presence of etalons is consistent with Southwest Sciences' prior experience with nearly all diode laser applications and explains why we target a minimum detectable absorbance of 1×10^{-5} (1 Hz) for field applications even though theoretical noise limits are $\sim 1 \times 10^{-8}$ for typical laser powers and detector characteristics. More importantly, these feasibility results imply that there is probably no performance penalty associated with frequency modulation multiplexing. Additional shot noise associated with having more than one laser impinging on the detector is exceeded by the etalons.

As the last test of frequency modulation multiplexing, Fig. 4 verifies no measurable cross-talk between the two demodulations. The CO and CO_2 spectra were acquired simultaneously using the apparatus depicted in Fig. 2. There is no excess noise or residual signal due to the CO peak in the CO_2 trace and *vice versa*.

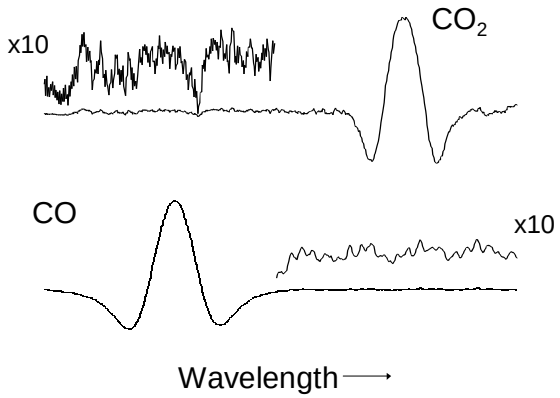

Figure 4 - CO and CO_2 spectra acquired using modulation frequency multiplexing.

The spectra acquired to demonstrate modulation frequency multiplexing (*e.g.*, Figs. 2-4) were not been scaled to the DC laser power, I_0 in Eq. (1). But, long term operation of commercial instruments would require dividing the WMS signal by the laser power in order to get the correct absorbance. Measurement of I_0 is straightforward when only one laser is impinging on the detector; we just measure the total photocurrent passing through the photodiode. For applications of

modulation frequency multiplexing, we anticipate using an indirect measurement of laser power: modulation of the laser current introduces amplitude modulation as well as wavelength modulation, and the magnitude of the amplitude modulation signal is an easily calibrated measure of the laser power.

5. Construction and testing of a commercial prototype

The next step in demonstrating the effectiveness of the diode-laser-based technology for early detection of fires is construction of a stand-alone prototype system for field testing. That work, now in progress, includes simultaneous detection of carbon monoxide, carbon dioxide, and hydrogen cyanide. Target detection limits for the three gases are 30 ppm for CO and CO_2, and 1 ppm for HCN. Key aspects of the prototype system include:

- Modularity. Each laser system operates independently while reporting gas concentrations and operating to a central computer using standard serial communications protocols.
- Digital signal processing (DSP) technology. A stand-alone, DSP single board computer controls each laser system and provides numerical demodulation of the detector signals as well as data reduction of the resulting wavelength modulation spectra. The DSP hardware including four analog-to-digital converters (200 kHz, 16 bits), four digital-to-analog converters (also 200 kHz and 16 bits), and two RS-232 serial ports provides a compact, low cost control and signal processing platform.
- Line locking. Stable, long-term performance of each laser system is guaranteed, in part, by using small optical cells filled with the target gases to provide a wavelength standard for active wavelength control of each laser.
- $1f$ power measurements. Accurate measurement of wavelength modulation spectra requires separate measurement of the $2f$ signal and "DC" power components of each laser's contribution to the overall photodiode output. The present approach uses the amplitude modulation that occurs synchronously with the laser's wavelength modulation to provide a frequency-dependent signature for measuring separately each laser's power reaching the photodiode.

Each DSP system is programmed to act as a digital lock-in amplifier. The laser modulation waveform is a modified square wave (the upper trace in Fig. 5). In theory, the $2f$ signal is $(a + b) - (c + d)$ where the time periods a, b, c, and d are noted in Fig. 5. In practice, this simple computation requires no electronic phase delays between the modulation waveform and the photodector output. A more useful approach, and the one used in the prototype instrument, requires digitizing the detector output at twice the frequency used for the modulation waveform–indicated by the vertical digital lines–and obtaining the vector dot products of the digitized signal with a pseudo-sine vector and with a pseudo-cosine vector. The $2f$ signal is the sum of the two dot products weighted by a demodulation phase. This calculation is repeated at each wavelength step in order to generate a complete $2f$ spectrum.

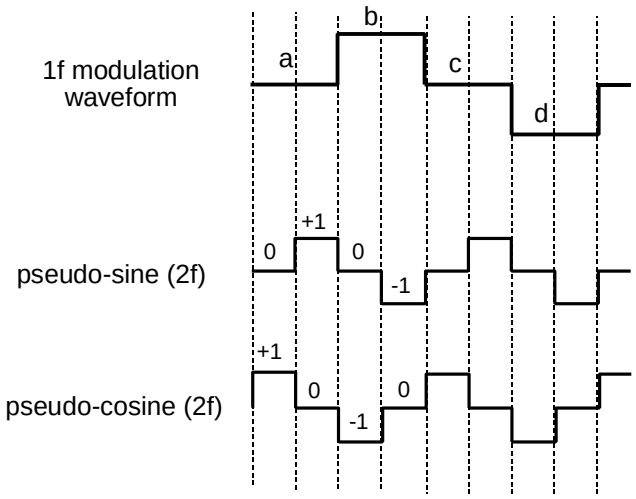

Figure 5 - Modified square wave modulation waveform (top) and the "in phase" (center) and "out of phase" (bottom) demodulation waveforms used for generating an all-digital wavelength modulation spectrum.

This demodulation approach is applied to both the signals from the reference cell and from a multipass cell similar to the Herriott cell used in the feasibility study. The signal from the reference cell is used for line-locking; a small offset is applied to the laser current control in order to keep the peak of the reference spectrum at the center of each scan. Figures 6 and 7 show the CO reference cell (line-locking) signal and the sample cell signal for 1000

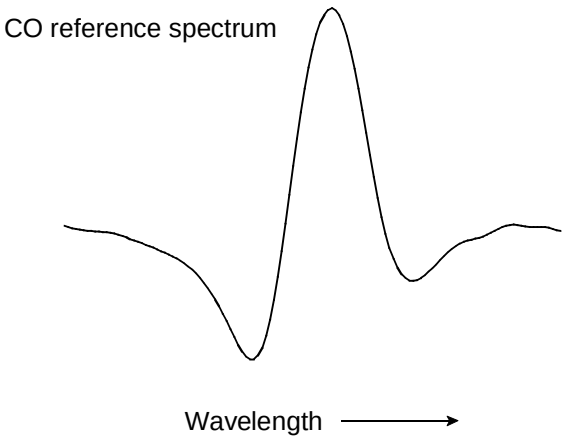

Figure 6 - CO reference cell $2f$ spectrum used for line-locking.

ppm CO, respectively. The spectrum in Fig. 7 shows the effects of unwanted optical interference fringes (etalons) which distort the line shape as well as introduce some high frequency noise. These etalons reflect mechanical problems in the alignment of the fiber optic collimating lens used to direct the combined laser beams into the sample cell. We anticipate that a modified lens mount should improve alignment stability and reduce the size of the etalons.

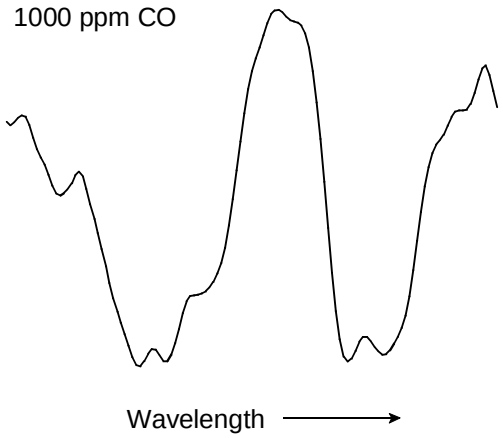

Figure 7 - $2f$ spectrum of 1000 ppm CO.

Gas concentration measurements are obtained from spectra such as Fig. 7 by representing each raw $2f$ spectrum as the sum of the "true" $2f$ profile, a DC offset, a baseline slope, and a baseline curvature term. This separation is shown pictorially in Fig. 8. The numerical decomposition can be performed quickly using a fast multilinear regression cast as a simple matrix equation:

$$raw = \mathbf{A} \cdot x \,, \qquad \textbf{(2)}$$

where **A** is the "library" matrix with columns comprising a representative $2f$ spectrum, the DC baseline offset, the baseline slope, and the baseline curvature, respectively. Vector x contains the coefficients identifying the amounts of the four terms that make up a given raw spectrum. Solution of the matrix equation (2) is straightforward,

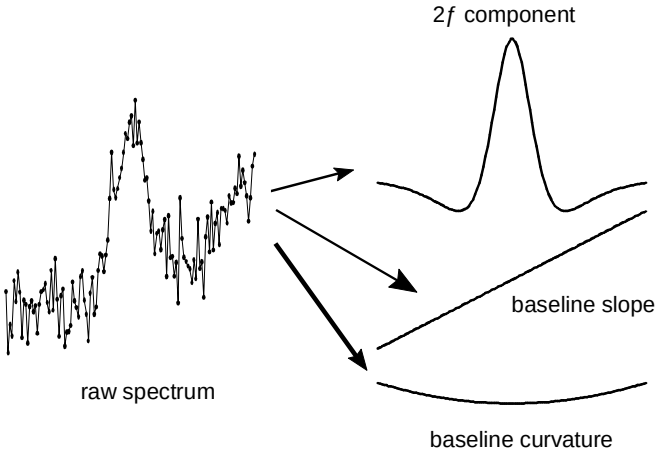

Figure 8 - Decomposition of raw $2f$ spectrum into the target $2f$ component plus a baseline slopes and curvature terms. The baseline offset term is not shown.

$$x = \left(\mathbf{A}^{\mathrm{T}}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathrm{T}} \cdot raw \ , \qquad \textbf{(3)}$$

and the matrix $(\mathbf{A}^{\mathrm{T}}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}$ can be calculated beforehand. In practice, only the first element of vector x is important – the magnitude of the $2f$ component within the raw spectrum – which is simply the dot product of the first row of $(\mathbf{A}^{\mathrm{T}}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}$ and the vector *raw*. The first row of $(\mathbf{A}^{\mathrm{T}}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}$ is stored on disk within the host computer and is downloaded to the DSP board soon after the RS-232 link is established.

Long term detection limits are presently an order of magnitude worse than the target levels due to problems in maintaining optical alignment in the sample Herriott cell. We are now redesigning one of the key optical mounts with the expectation of significant improvement in pointing stability and, concurrently, gas detection sensitivities.

6. Acknowledgment

This work supported by NIST under Phase 1 and 2 SBIR contract 50-DKNB-7-90149.

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